REVIEW

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Distribution mapping of major invasive plant species of India and their role in ecosystem alteration: a systematic review

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Abstract
Invasive plant species (IPSs) are highly dominant and spreading frequently due to their rapid growth, reproduction, broad tolerance range, and high dispersal ability. They are the second-most dangerous threat to the world's biodiversity and are of non-native origin. They are widely introduced, either intentionally or unintentionally, through anthropogenic activities throughout the world, which have an impact on a country's biological diversity and economic security. Rising IPSs have a significant negative impact on ecosystem goods and services provided by the agricultural, forestry, and aquatic sectors by disrupting habitat structure and function. These IPSs disrupt the biogeochemical cycle, the cycle of fire, the pattern of plant succession, the process of plant regeneration, and the overall forest dynamics. Remote sensing presents a significant potential for scientists and researchers working on invasive biology, resource executives, and policy planners to create prediction models based on invasive risk assessment and early detection methods. Substantial progress can be made in identifying, modeling, and mapping IPSs across various ecosystems and habitats by combining data from field sampling with remote sensing technologies. Various multispectral remote sensing tools are presently being used for IPS mapping and monitoring purposes, such as Thematic Mapper, Enhanced Thematic Mapper Plus, etc., to record the current status of IPSs in forest ecosystems. Import restrictions, import tariffs, and risk management techniques are the three most commonly used policies for preventing trade-based introductions of IPSs. They can be managed and controlled in a variety of physical, chemical, biological, and cultural ways, but early detection and decisive action with species-specific eradication measures will be the best way to prevent the native plant species loss and to preserve biodiversity.

Keywords Invasive plant species, Status, Impacts, Remote sensing, Mapping and monitoring, Management strategies

1 Introduction

Native plant communities are significantly impacted by invasive plant species (IPS), which spread and cause instability in both agricultural and natural ecosystems [134]. They achieve high levels of prevalence within their food chain in a new community [183], which significantly alters the way in which the forest ecosystem's functions [40]. Intentional or unintentional introduction of IPSs may significantly depend on human needs [84], which has serious risks for the local biodiversity, ecosystem services, and environmental quality [13, 72]. The Convention on Biological Diversity (CBD) considers the biological invasion of IPS to be the second-most serious concern after habitat destruction [167], which is wrecking economic and ecological havoc around the world [179]. This has become a serious ecological and environmental policy challenge because of the unprecedented rates of native species displacement in both terrestrial and marine ecosystems [152]. The population structure of invasive species, their effects, and their interactions with ecological factors like weather and disturbances all change over time [165]. IPS alters the hydrology, fire dynamics, carbon cycling and storage, and biogeochemical cycling of the encroaching ecosystem, degrading it structurally and functionally [102]. Before exhibiting abrupt changes like local population outbursts or population expansion, which may be brought on by changes in the invasive species, their abiotic environment, and their biotic interactions, they persist in low numbers for prolonged periods of time [28]. IPSs have characteristics such as acquiring a lot of relative biomass, producing a lot of seeds, and being better able to withstand adverse environmental conditions that affect ecosystem processes [182]. They also have high utilization potential for several purposes such as edibles, medicines, fodder, construction materials, bioenergy production, pest control, micro-climate and shade regulator, as well as soil stabilizes and reclaimers, which increases their economic value [15, 55, 130]. These potential socio-economic advantages of certain IPSs in urban and village areas aided their rapid spread in forests and led to biodiversity loss [19, 178]. The outspread of IPSs results in menacing human health, economy, and biodiversity of the region, although some of them are useful as a curative for different ailments like ulcers, infections, inflammation, etc. [6]. Native plants are frequently outcompeted by IPSs for water, nutrients, and light, which raises their management costs and has a detrimental effect on livestock and agricultural production [76, 168]. Understanding different variables that influence the growth and development of IPS over time may help in devising strategies to modify and rehabilitate the invaded ecosystems [142]. Biological control is one of the techniques which may be employed alone or in conjunction with other management techniques, such as physical or chemical processes, that help in suppressing IPSs [112]. A number of policies, risk assessments, and laws have been put in place to control and regulate the growth as well as proliferation of IPSs in natural forests [136]. Displacement of polluted soil and construction materials, as well as the construction of forest roads, encourages the spread of IPSs and their propagules [118]. Poor individual performance and reduced species diversity resulting in irreversible alterations of understorey vegetation are commonly linked to the spread and growth of IPSs in a particular area [120]. Anthropogenic activities, dissemination of ornamental plants, development of new technologies, and increasing trade and transport globally are some of the major factors contributing to the spread and propagation of IPSs worldwide [189].

Tropical forests cover less than 10% of the Earth's surface; meanwhile, they are the largest habitat of terrestrial biodiversity [49]. India has 10 distinct biogeographic areas, which contribute to the country's abundance of natural resources [161]. A sum of 360 million locals residing in and around the forest fringes directly depends upon forest products and services, deploying vast pressure on the ecological diversity of forests [88, 131]. The ability of self-fertilization, significant phenotypic plasticity, and production of enormous soil seed banks are the characteristics that help IPS spread and colonize new areas [23]. According to the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) of the United Nations, biotic invaders threaten around one-fifth of the Earth's surface, including the world's biodiversity hotspots [66]. Dispersal of pathogens through the import and export chains, seed contamination, and anthropogenic activities are one of the primary causes of the introduction of IPSs [26]. In this way, compared to low-income countries, high-income countries recorded 30 times more IPSs [140]. IPSs play a crucial role in the long-term sustainability of forest ecosystems, and it has direct relevance to the conservation management of forests. Therefore, a systematic review of a total of 177 articles related to IPSs' diversity, distribution, management, and control strategies was conducted to determine the role of IPSs in ecosystem alteration.

2 Materials and methods

A non-exhaustive and systematic literature survey (from both offline and online information systems) of papers, research articles, and other book materials was gathered concerning the diversity and abundance of IPSs in India, the impact of IPSs on the forest ecosystem and productivity, the relationship between IPSs with native plant species, management of IPSs, the importance of remote sensing and GIS in mapping and monitoring of IPSs, and policies for the control and monitoring of IPSs. To extract current information, the review procedure entailed choosing relevant subject areas and focusing on suitable keywords. The sources for online material, search engines and databases like Scopus, Google Scholar, Web of Science, ResearchGate, Science Direct, Springer Link, and other official websites have been explored for the thorough selection of articles having the specific keywords. Primarily, the main conclusions and abstracts of secondary sources were critically reviewed to determine their applicability to the current study. Literature based on topics such as IPSs-based research work, applications of IPSs in different sectors, the contribution of different disturbances in proliferating the growth and development of IPSs, quantification of impacts of IPSs, and distribution of IPSs was included. Whereas, literature that is not directly related to IPSs study, such as bioactive compounds in IPSs, suitability studies, etc., was excluded. Thereafter, according to the study's research framework, the suitable contents were sorted (e.g., significant findings, texts, and abstracts). The pertinent cited literature in this review covered the development of IPS science over the previous decades. A specified methodology like PRISMA was used for gathering and selecting information sources (Fig. 1). Furthermore, the selected references were examined and summarized to elaborate the narrative based on the distribution of IPSs in India, the current scenario, the impact on the forest ecosystem, monitoring and future prediction strategies, suitability mapping, and management strategies. The cited literature in this review article was published between 1991 and 2023.

In the first step, a sum of 1,53,212 hits for scientific references and preprints had been quantified based on research criteria, which include different research articles, reviews, conference proceedings, reports, and book chapters. Further, 1,37,125 hits had been removed as duplicates, not studied in India, and not concerned with the studies. The remaining 16,087 hits had been selected based on title, keywords and abstract. Later on, a sum of 9,170 hits had been removed as inappropriate, such as not directly mentioning

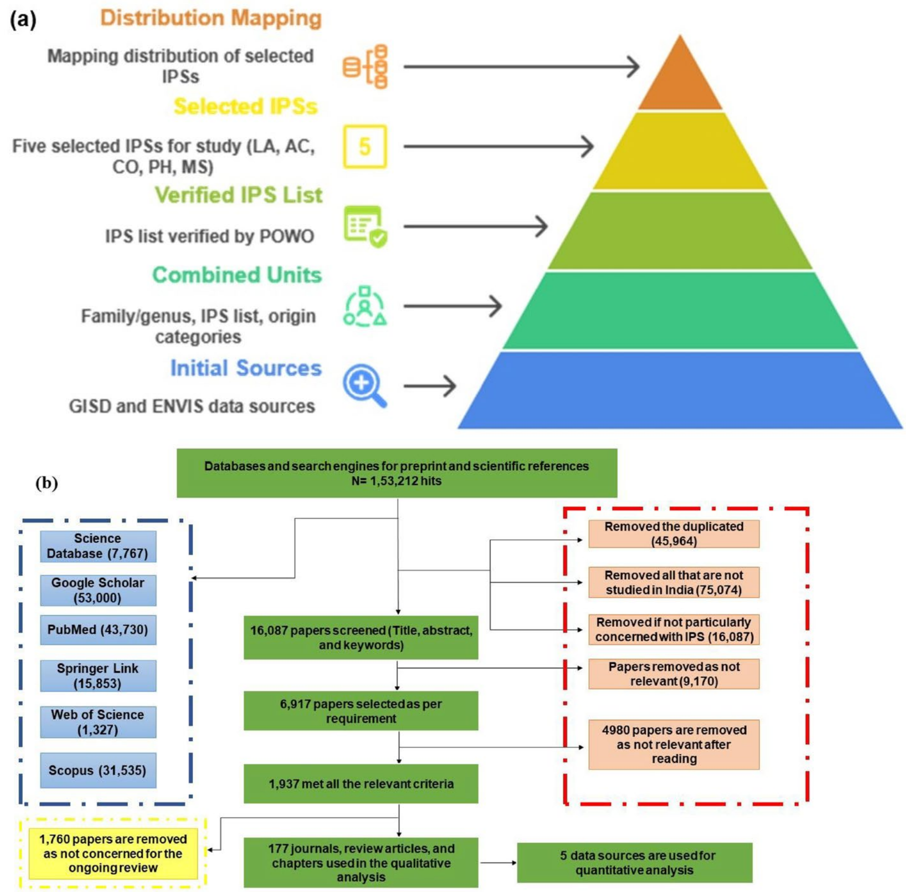

Fig. 1 **a** Sources of information and Data collection process, and **b** PRISMA approach for the gathering and selection of information sources

IPSs in the introduction section, research methods or conclusions. Further, 6,917 hits had been selected as per the requirement. Later, 4,980 hits were removed as non-relevant after reading, such as research works based on bio-chemical studies of IPSs, and 1,937 hits were selected for further classification. In the second step, a sum of 1,760 hits had been deducted as not relevant for the present review, such as suitability studies of IPSs, compounds present in IPSs, etc., and at last, 177 articles and papers had been selected for qualitative analysis, and 5 databases were used for quantitative analysis.

Global Invasive Species Database (GISD) and Environmental Information System Resource Partner on Biodiversity (ENVIS) Centre, Ministry of Environment, Forest and Climate Change (MoEFCC), Plants of the World Online (POWO).

3 Status of IPS in Indian forests

A total of 144 IPSs are recorded in India, belonging to 107 genera and 40 families, based on the online database of invasive species available at the Global Invasive Species Database (GISD) [50] and the Environmental Information System Resource Partner on Biodiversity (ENVIS) Centre [41], Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, after verification at Plants of the World Online (POWO) [135] (Appendix Table 6). The present study reports a very low species-to-genus ratio (1.35) compared to earlier reports of IPSs documented in India [79,

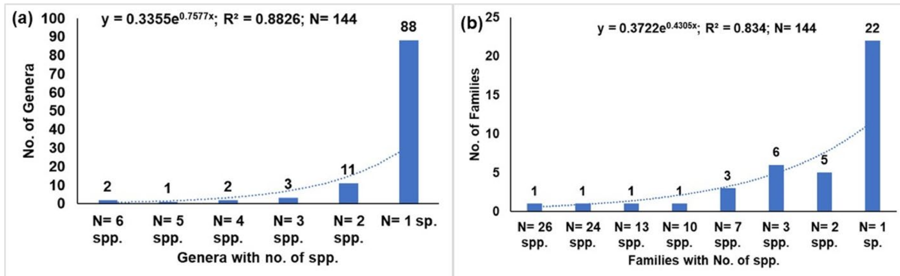

Fig. 2 Distribution of **a** genera and **b** families according to the number of IPS documented in India (available at GSID and ENVIS after verification at POWO)

Table 1 Species richness of IPS in India as reported by various authors

Species richness of IPS	Genus richness	Family richness	Species-to-genus ratio	Most dominant families	Sources
144	40	107	1.35	Asteraceae (26 spp.) Fabaceae (24 spp.), Solanaceae (13 spp.), Poaceae (10 spp.)	Present research
1599	161	842	1.90	Asteraceae (134 spp.) Papilionaceae (114 spp.), Poaceae (106 spp.), Caesalpiniaceae (64 spp.), Solanaceae (63 spp.)	Khuroo et al. [79]
173	117	44	1.48	Asteraceae (33 spp.), Papilionaceae (15 spp.), Convolvulaceae (10 spp.), Caesalpiniaceae (9 spp.), Solanaceae (9 spp.)	Reddy [143]
161	-	37	-	Asteraceae (29 spp.), Fabaceae (22 spp.), Convolvulaceae (13 spp.), Amaranthaceae (12 spp.), Solanaceae (10 spp.)	Tripathi et al. [171]

143]. The species-to-genus ratio reflects the rate of species diversification,a high ratio indicates greater species diversity [150], while a low ratio suggests that vegetation took longer to develop [146]. The family Asteraceae exhibits the highest diversity of IPSs with 26 species, followed by Fabaceae (24 spp.), Solanaceae (13 spp.), Poaceae (10 spp.), with 22 families being monotypic (Fig. 2a). Similarly, the genera Solanum and Senna each contribute the highest species diversity with 6 species each, followed by *Acacia* with 5 spp., and *Alternanthera* and *Euphorbia* with 4 spp. each, while 88 genera are monotypic (Fig. 2b). There is considerable disagreement regarding the total number of IPSs in India. Some researchers report 1599 IPSs belonging to 842 genera and 161 families during 1890–2010, with Asteraceae as the most dominant family (134 spp.), followed by Papilionaceae (114 spp.), Poaceae (106 spp.), Caesalpiniaceae (64 spp.), and Solanaceae (63 spp.) [79]. Others have reported 173 IPSs belonging to 117 genera and 44 families between 2003 and 2007, with Asteraceae again as the most species-rich family (33 spp.), followed by Papilionaceae (15 spp.), Convolvulaceae (10 spp.), Caesalpiniaceae (9 spp.), and Solanaceae (9 spp.) [143] (Table 1). The significant variation in IPS counts between Khuroo et al. [79] and other studies results from differences in the definition and categorization of IPS. The present study adopts the definitions and categorizations used by GISD and ENVIS. Additionally, species previously classified as causal, according to Pyšek et al. [138], are now considered invasive. The majority of IPSs originate from Tropical America (41.67%), followed by Tropical South America (6.25%), Brazil (3.47%), and Tropical Central America (2.78%). Major IPSs of Tropical American origin include *Ageratum conyzoides* L., *Lantana camara* L., *Chromolaena odorata* (L.) R.M. King &

H. Rob., and *Mesosphaerum suaveolens* (L.) Kuntze. IPSs from Tropical South America include *Senna tora* (L.) Roxb., *Senna occidentalis* (L.) Link, *Passiflora foetida* L., *Peperomia pellucida* (L.) Kunth, and *Portulaca oleracea* L. (Appendix Table 6).

In terms of area covered by the IPSs, Madhya Pradesh has the highest coverage (5391 sq. km), followed by Karnataka (2860 sq. km), Chhattisgarh (1939 sq. km), Maharashtra (1640 sq. km), and Tamil Nadu (1515 sq. km). Jammu & Kashmir is the most IPS-invaded union territory, with the highest area coverage (102 sq. km) [44]. Among the Himalayan states, Assam has the highest IPS invasion (895 sq. km), followed by Arunachal Pradesh (761 sq. km) and Uttarakhand (562 sq. km) (Fig. 3). Regarding the percentage change in area coverage by IPSs in 2021 compared to 2019, eight Indian states showed an increase, with the highest positive growth of 3.70% in Madhya Pradesh, followed by Maharashtra (0.56%), Arunachal Pradesh (0.25%), Odisha (0.19%), Tripura (0.12%), Mizoram (0.04%), and Goa and Sikkim, both with a 0.02% increase. The majority of Indian states and union territories (22) experienced a decrease in percentage area coverage (Fig. 3c). This trend may be attributed to effective policy interventions against invasive species undertaken by the state forest departments.

4 Invasives (IPSs) of Jharkhand: a case study

Invasive species (IPSs) mapping, documentation, diversity, and quantitative assessment are prioritized in the majority of Indian research, along with habitat identification through spatial modeling [126]. Other crucial aspects of research on Indian invasive plant species include chemical analysis, ethnobotanical significance, and allelopathic effects [180]. Besides that the majority of Indian research focuses on invasions in urban areas, protected areas [58, 158], forests, aquatic ecosystems [71, 115], and along the roadside, while the most extensively researched Indian invasive species are *L. camara, C. odorata, Senna tora* (L.) Roxb., and *Senna alata* (L.) Roxb. [36] (Table 2).

Jharkhand ranked 11th out of all Indian states and union territories in terms of forest cover (29.61%) and is known for having abundant forest resources due to its origin, diverse physiographic conditions, and a climate that is dominated by tropical deciduous forests with a high density of *Shorea robusta* C.F. Gaertn. [44, 89]. Numerous ongoing anthropogenic disturbances are affecting the forests of Jharkhand, including changes in land-use patterns, illegal timber felling, fuelwood collection, several non-timber forest

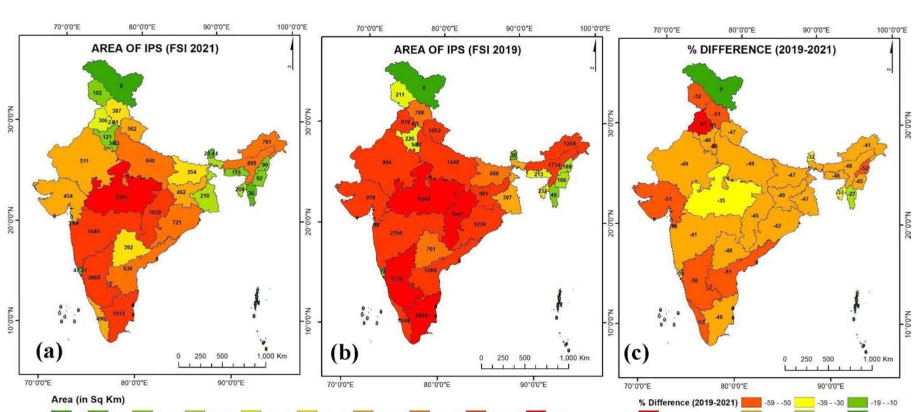

Fig. 3 Status of IPS in different Indian states and union territories based on FSI report **a** 2021, **b** 2019, and **c** Per cent change from 2019 to 2021

Table 2 Some important literature reviews from Indian forests and the forests of Jharkhand, particularly

Theme of research	Major findings	References
Indian Forests		
Distribution pattern, future projection for 2050 and 2100, and habitat suitability of *C. odorata* and *Tridax procumbens* L. using MaxEnt Modeling in Indian scenarios	Except for the South-East region, *C. odorata* can invade all over India. At the same time, *T. procumbens* can invade west-central and central regions, and moisture availability and temperature of a region play an important role in the distribution of both the IPSs in India	[126]
Diversity of IPSs in the Indian Himalayan Region	A total of 190 IPSs have been recorded from 112 genera and 47 families, of which 18 IPSs are introduced intentionally and 172 by other means	[21]
Quantifying the diversity and importance of IPSs in Uttar Pradesh, India	152 IPSs have been recorded, of which 73% are of Tropical American and 10.5% are of Tropical African origin	[162]
Quantifying the use of *L. camara* in Southern Indian states of Andhra Pradesh, Karnataka, and Tamil Nadu	70% of the total population of Chamrajanagar, Dindigul, and Chittoor districts are using *L. camara* for economic purposes and have higher occupational opportunities than the non-users	[74]
Diversity and density changes in the vegetation of the N-W Himalayan region of India	Out of the total plant diversity, 9.4% were IPSs, and *P. hysterophorus* was the most dominant IPS, followed by *A. conyzoides*	[84]
Medicinal importance of IPSs in western parts of Madhya Pradesh during 2008–2013	102 IPSs were implicated in the treatment of 37 different ailments in MP	[180]
Impact of *L. camara* on bird community in Karnataka	Bird populations are inversely proportional to the density of *L. camara*	[5]
Ethno-medicinal importance of IPSs in Kozhikode district, Kerala	The majority of the 28 IPSs harm floristic diversity, while some of them have medicinal utilities	[129]
Documentation of IPSs in urban, agricultural, and protected areas in Bilaspur, Chhattisgarh, during 2014–2016	A total of 83 IPSs have been recorded in Bilaspur, of which the majority are found in urban areas (34.58%), followed by protected areas (29.16%) and agricultural areas (25%)	[158]
Documentation of IPSs in Tamil Nadu	279 IPSs have been documented, of which Nilgiri has the maximum invasion by 146 IPSs	[166]
Documentation of IPSs in Udhagamandalam, Tamil Nadu	A total of 25 ornamental plants and 43 spontaneous weeds have been documented in Ooty township	[114]
Documentation of IPSs in Rourkela, Odisha	165 IPSs have been recorded with ethnomedicinal and ecological significance	[103]
IPSs in Protected Areas of India	11 IPSs have been reported in the PAs of India using different databases like Agricola, Web of Science, and Journal of Tropical Ecology	[58]
Identification of Indian hotspots of IPSs through Niche Modelling using the GBIF database	49% of the total geographic area of our country is suitable for invasion, and 19 out of 47 ecoregions are identified as the invasion hotspots	[1]
Distribution of *L. camara* and *S. tora* using modeling protocols (generalized additive, generalized linear, and maximum entropy for 2050 and 2100	*L. camara* will invade the Eastern and Western Himalayas as well as Western Ghats regions of India, while *S. tora* will invade Central Indian regions, and availability of moisture and suitable temperature will determine the abundance of both species	[127]
Comparative study of the characteristic differences between natives (*Berberis asiatica* Roxb. Ex DC., *Pyracantha crenulata* (D. Don.) M. Roemer, and *Rubus ellipticus* Sm.) and IPSs (*Ageratina adenophora* (Spreng.) and *L. camara*) in Central Himalaya	Specific leaf area, leaf water content, chlorophyll content, relative growth rate, nitrogen and phosphorus content, leaf mass ratio, shoot mass ratio, nutrient uptake, nutrient use efficiencies, etc., are high in IPSs as compared to native plant species	[87]

Table 2 (continued)

Theme of research	Major findings	References
IPS abundance and distribution in Manas National Park, Assam	*Mikania micrantha* Kunth and *C. odorata* are the most dominant species. Out of 11 variables, 4 variables ($R^2 = 0.511$) are significant for the growth of *M. micrantha,* and 2 variables ($R^2 = 0.124$) are significant for the growth of *C. odorata*	[34]
Composition of oil extracted from leaves and flowers of *L. camara* using GC and GC–MS collected from Kukrail Reserved Forest, Lucknow	Major constituents of leaf were germacrene-D and ɣ-elemene, while β-elemene and germacrene-D of flowers	[77]
Forests of Jharkhand		
Threats of IPSs in the natural forests of Betla National Park	14 IPSs were responsible for altering the ecosystem and impacting the livelihood of local communities in and around the forest, where *L. camara* and *P. hysterophorus* were the most dominant IPSs	[92]
Documentation of IPSs in Latehar and Hazaribagh districts	41 IPS were recorded from both forested and non-forested areas in both the districts where *L. camara* holds the highest density in open forests (2917 and 43 ind. ha^{-1}) and dense forests (3535 and 117 ind. ha^{-1}) in Latehar and Hazaribagh districts, respectively	[37]
Study of aquatic and semi-aquatic IPSs from 2011 to 2016 in Santhal Pargana	Dumka district is invaded by 30 semi-aquatic and aquatic IPSs that have ethnomedicinal importance	[115]
Ethnomedicinal importance of IPSs in Latehar and Hazaribagh districts	Ethnomedicinal importance of selected IPSs, including *A. conyzoides*, *Argemone mexicana* L., *Calotropis procera* (Aiton) W.T.Aiton, *Senna alata* (L.) Roxb., *S. tora*, *Cuscuta reflexa* Roxb., *Datura metel* L., *Eclipta prostrata* (L.) L., *Emilia sonchifolia* (L.) DC., *C. odorata*, *M. suaveolens*, *Leonotis nepetifolia* (L.) R.Br., *Opuntia stricta* (Haw.) Haw., *Scoparia dulcis* L., *Sida acuta* Burm.f., *Solanum torvum* Sw., and *T. procumbens* had been recorded for a range of ailments	[36]
Climate change and dispersion dynamics of *C. odorata* and *L. camara* using MaxEnt modeling in Central and Eastern Indian Chhattisgarh, Jharkhand, and West Bengal	*L. camara* (31%) has invaded more areas compared to *C. odorata* (24%), while in 2050, the invasion of *C. odorata* will increase by 1.53% compared to *L. camara*	[157]
Morphology, palynology, and anatomical study of *Ipomoea carnea* Jacq	The presence of spongy parenchyma and radially arranged cambium cells helps *I. carnea* to easily invade both terrestrial and aquatic ecosystems	[116]
Identification and future projection of the area that is prone to the invasion of *M. suaveolens* using MaxEnt from 2020 to 2050	Dry tropical deciduous forests are at high risk of *M. suaveolens* invasion, and presently, 9.09% of the area is at high risk, while in future (2050) it may range from 10.48 to 11.32%	[139]
Threats of aquatic IPSs to the limnetic systems of Jamtara district	Documented 7 aquatic IPSs, viz., *Alternanthera philoxeroides* (Mart.) Griseb., *Cyperus difformis* L., *C. iria* L., *E. prostrata*, *Oxalis corniculata* L., *Typha domingensis* Pers., and *Pontederia crassipes* Mart	[71]

products, looping, forage removal, rock mining, grazing, fire, clearing large tracts of forest for human settlements, agricultural practises, road networks, and industrial units [91]. Additionally, the predominance of invasives like *L. camara* is also reported in the sal forests of Jharkhand [90]. A sum of 41 IPSs had been documented from both forested and non-forested areas of Latehar and Hazaribagh districts, out of which *L. camara* holds the highest density (2917 ind. ha^{-1} and 3535 ind. ha^{-1} in forested and non-forested areas, respectively, in Latehar as well as 43 ind. ha^{-1} and 117 ind. ha^{-1} in forested and non-forested areas, respectively, in Hazaribagh district) [37]. Landscape restoration efforts were initiated in the mining degraded areas but no such restoration efforts are documented in both the districts of Jharkhand based on the impact of IPSs. Only 14 IPSs had been recorded in protected forests (Betla National Park), where the growth and development of *L. camara* and *Parthenium hysterophorus* L. majorly contribute to the alteration of ecosystem structure and function [92]. Species such as *L. camara*, *M. suaveolens*, and *C. odorata* are quite prominent and harm native species due to their high density, rapid growth, and high abundance in the forests of Jharkhand [93]. East, south, and north-west parts of Jharkhand are majorly invaded by *L. camara* (87%) [170], followed by *M. suaveolens* (9.09%), and dry tropical forests are at high risk of invasion [139]. The ecological niche modeling approach was applied to determine the habitat suitability of *L. camara* and *C. odorata* in the Central and Eastern Indian states of Chhattisgarh, Jharkhand, and West Bengal and a total of 31% area is invaded by *L. camara,* while *C. odorata,* invaded 24% area; however, the area of invasion by *C. odorata* will increase by 1.53% as compared to *L. camara* in 2050 [157]. Similarly, the state of Jharkhand is also invaded by some aquatic invasives and a total of 30 aquatic IPSs were reported in Dumka district [115], while 7 aquatic IPSs were reported in Jamatra district [71] (Table 2).

5 Distribution of selected Indian invasives and their role in ecosystem alteration

The present review emphasized selected IPSs, including *A. conyzoides*, *L. camara*, *P. hysterophorus*, *M. suaveolens*, and *C. odorata* (Fig. 4). Based on the data available at the GBIF portal [48], the Indian distribution of all these five species is mapped and has found that *L. camara* and *P. hysterophorus* are the most widely distributed in India, barring the top Himalayan regions and extremely arid regions of Gujarat and Rajasthan, while the major hotspotsCountries throughout the world have set for *C. odorata* and *L. camara are* the western ghat regions (Fig. 5). The growth form, key features, habitat preference, notable impacts and traits, and hotspots in India of all the selected species were summarized (Appendix Table 7).

Fig. 4 **a***Ageratum conyzoides* L. **b***Lantana camara* L. **c***Parthenium hysterophorus* L. **d***Mesosphaerum suaveolens* (L.) Kuntze **e***Chromolaena odorata* (L.) R.M.King & H.Rob.

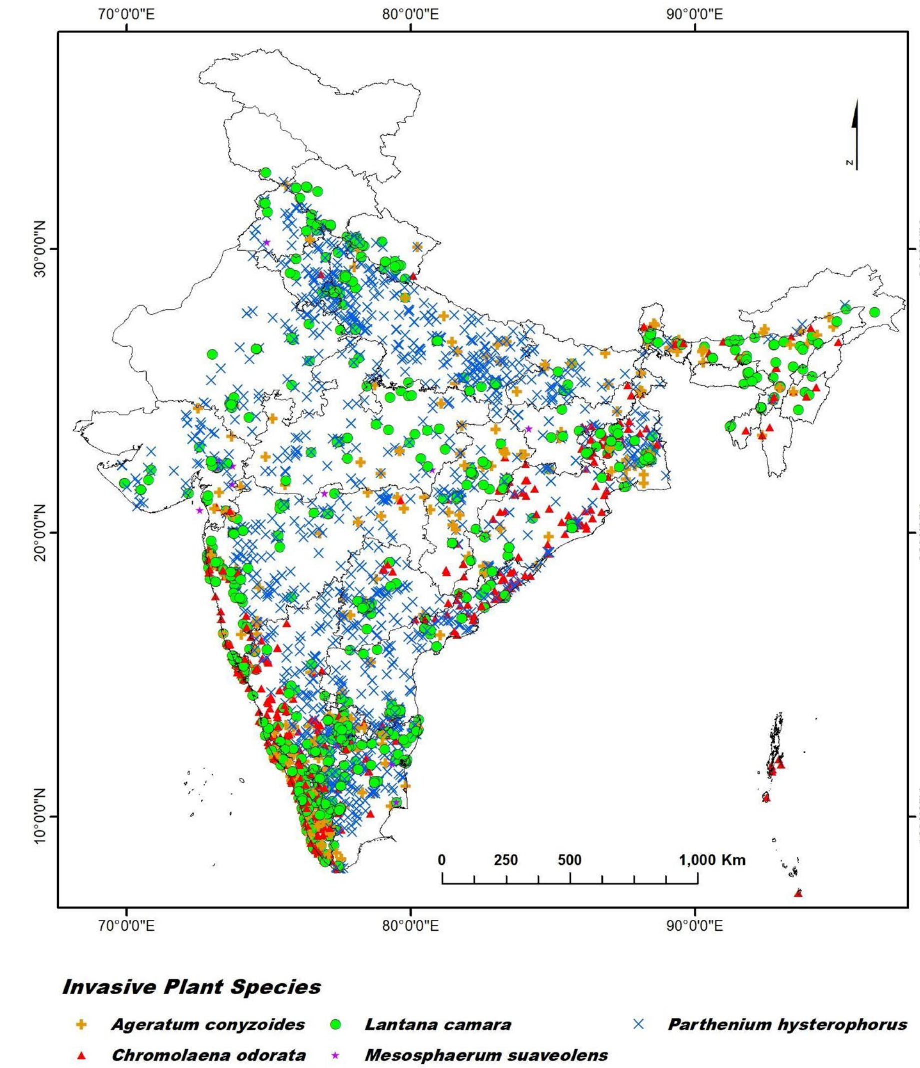

Fig. 5 Indian distribution of selected IPSs (*Ageratum conyzoides* L., *Lantana camara* L., *Parthenium hysterophorus* L., *Chromolaena odorata* (L.) R.M.King & H.Rob., and *Mesosphaerum suaveolens* (L.) Kuntze based on the data available at the GBIF portal

5.1 *Ageratum conyzoides* L.

A. conyzoides is a Tropical American-originated species belonging to the family of Asteraceae. It was introduced in India as an ornamental plant in 1860 [119] and primarily invaded forests, grasslands, pastures, agricultural fields, and wastelands. It is responsible for decreases in species richness (32.10%) in the Shivalik regions of the Indian Himalayas [38]. It successfully invades Indian forests due to its quick growth rates, shortened life cycles, resistance to drought, allelopathy, stronger competitive abilities, and increased reproductive capacity [83].

5.2 *Lantana camara* L.

L. camara is a woody shrub that also originated in Tropical America, belongs to the family Verbenaceae, and is one of the most destructive IPSs in the world [155]. It prevents the growth and development of native plants in forests because of its perennial reproduction, high rate of germination, and presence of various allelochemicals like lantadene [157]. This broadly eco-tolerant species was introduced to India in 1809 [83] and adversely impacted the stratification, pollination, and regeneration processes in dry tropical deciduous forests [121]. The high rate of proliferation and wide range of adaptability to new habitats under different climatic conditions [117] contributed to a 50% diminution in natural resources and cattle feed, and acted as a hindrance to the movement of people and livestock [153]. About 44% of forests in India are vulnerable to *L. camara* invasion, specifically those regions having high humidity, warm climate, and productive areas [117]. Anthropogenic activities, forest fires, open spaces, and disturbed areas are the major factors contributing to the spread of this species to the forests [170]

5.3 *Parthenium hysterophorus* L.

P. hysterophorus is a Tropical North American-originated species belonging to the family Asteraceae. It is the most toxic species that invades areas drastically by altering the soil quality, livestock and crop production, and forest biodiversity of the major Indian forests [16]. This species significantly reduces crop production (50%) and simultaneously reduces the production of pasture by 90% [78]. In a particular agroecological region, *P. hysterophorus* negatively impacts the composition, richness, quantity of native plant species, and organization of native floral communities [16].

5.4 *Mesosphaerum suaveolens* (L.) Kuntze

This Tropical American-originated plant species, belonging to the family Lamiaceae, is considered a serious threat following *L. camara* in deciduous forests of India [156]. It poses a significant quantity of germination issues by producing allelochemicals and imperils the survival of native species and cattle rearing due to its uneven topographical distribution [139]. This species, a pantropical, fragrant herb with a propensity for perpetual growth, is an invasive plant that spreads quickly and threatens local biodiversity, especially vulnerable or endangered species [125]. In India, the Northeastern zone, the Andaman and Nicobar Islands, the Vindhyan, and the Deccan plateau are severely invaded by this species [139].

5.5 *Chromolaena odorata* (L.) R.M.King & H.Rob.

C. odorata originated in Tropical America and belongs to the family Asteraceae is one of the fastest-spreading IPSs in subtropical and tropical regions [85] due to its extraordinary tolerance and adaptation to a range of environmental conditions [86]. In 1845, as an ornamental shrub, *C. odorata* was introduced into the botanical garden of Kolkata, India, and later it became invasive [173]. It poses a severe threat to native plant species, farming, and livelihoods due to its high proliferation rate and the presence of the soil fungus *Fusarium semitectum* that alters the growth and germination processes in major endemic plants [105]. Precipitation, temperature, and physiographic factors are some of the measures that estimate the distribution pattern of this species in India [12].

6 Impacts of invasive plant species on forest composition

The success of invasive plant species and their effects are significantly influenced by the biological characteristics of the species, the environmental circumstances of the invaded ecosystem, and the biological interactions with the receptive community [177]. IPSs pose various challenges in forest ecosystems, including hybridisation, disease transfer,

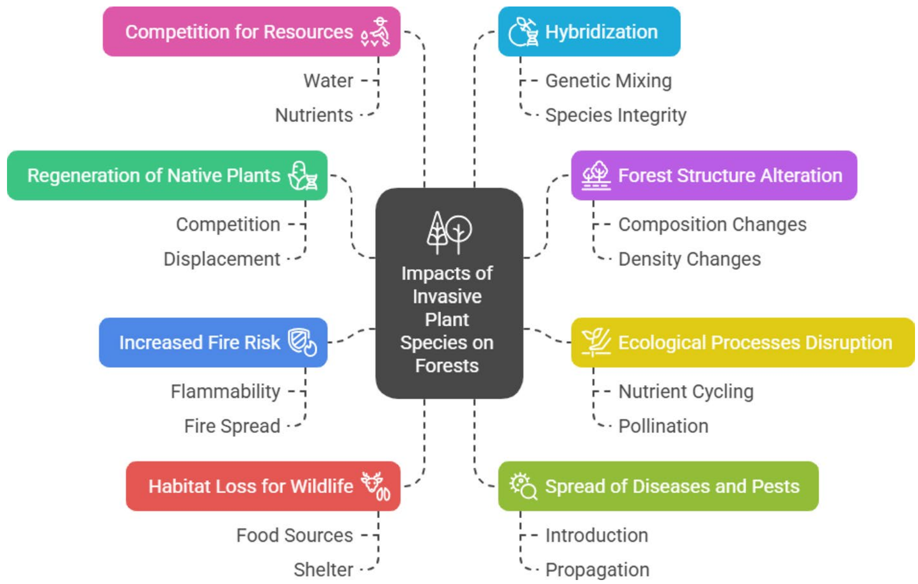

Fig. 6 Impact of IPSs on forests and their ecosystem functioning

Table 3 Selected Indian invasives and their impacts on ecosystem services and livelihoods

Name	Impacts	Source
Ageratina adenophora (Spreng.) R.M.King & H.Rob.	Enhances the association of microbial diversity in soil	[46]
Ageratum conyzoides L.	Degrade the structure, composition, and soil quality by increasing phenolic content	[38]
Chromolaena odorata (L.) R.M.King & H.Rob.	Adversely affect the native vegetation	[159]
Lantana camara L.	Alters the physicochemical properties of soil	[159]
Mesosphaerum suaveolens (L.) Kuntze	Damage the native vegetation by substituting the threatened or vulnerable species	[125]
Mikania micrantha Kunth.	Harmful effects on the environment also have a major role in changing the climate	[54]
Opuntia stricta (Haw.) Haw.	Affects the environment, health and socio-economic livelihood	[154]
Parthenium hysterophorus L.	Distributed pan-tropically and plays a major role in climate change	[159]
Prosopis juliflora (Sw.) DC.	Inhibits the growth and germination of native seedlings	[27]
Senna uniflora (Mill.) H.S.Irwin & Barneby	Negatively impacts plants, inhibiting the growth and germination of native plants' seedlings present in the surrounding area by its allelopathic effects	[73]

and species competition [110], all of which have serious socio-economic and health consequences [148] (Fig. 6). They have a greater impact on biodiversity, especially in protected areas [45], and increase the mortality of native tree seedlings while limiting regeneration through competition [59]. IPS dominance acts as an obstacle to forest restoration [30] and causes severe degradation of forest health by altering soil characteristics, fire frequency, hydrology, nutrient cycling, and biodiversity [185] (Table 3). The prevalence, composition, and timing of litter generation are mainly affected by the increasing population of IPSs, which change nutritional inputs, modify mineralization processes, and alter the structure and dynamics of plant assemblages [35]. Consequently, plant-soil interactions promote the spread of IPSs through their seedlings [2]. As IPSs adapt well to different environmental conditions, they reproduce in natural ecosystems and threaten native species' biodiversity by competing for resources and habitat [69].

IPSs proliferate throughout the protected areas of the Himalayan region, endangering wildlife by consuming their primary food sources and destroying habitats [69]. Fire is a natural and constant disturbance in forest diversity and growth, with IPSs acting as catalysts by increasing the frequency of fires in specific areas [95]. Global biota homogeneity caused by IPSs indirectly impacts ecosystems and their services [13] by hindering growth and development, depleting soil nutrients, and occupying space—affecting the structure and composition of native flora [69]. Although it is difficult to define the exact threshold for ecological degradation caused by IPSs because their impact tends to be cumulative and gradual rather than abrupt, and because reactions are often delayed and nonlinear, making threshold detection unreliable [57]. Additionally, impacts are site-specific, depending on local climate, soil type, and species composition, so the threshold in one ecosystem may not apply to another [53]. The socio-economic benefits of potential IPSs in rural and urban areas have encouraged their rapid spread in forests [174]. Land use and climate change-driven biotic invasions of flora hinder biomedical progress in reducing risks to human health [39]. IPSs are often difficult to eradicate and controlling their spread, while minimising impacts on agriculture, biodiversity, people, and the environment, usually requires long-term efforts [168]. Modern techniques such as the species threat abatement and restoration (STAR) metric, its derivatives, individual species-area relationship (ISAR) approach, diversity indices, richness measures, and habitat area mapping (AOH) over time, will assist in assessing species-specific ecological impacts, especially biodiversity loss, by quantifying the conservation status and vulnerability of individual species.

7 Remote sensing for IPS mapping and monitoring

Remote sensing has emerged as a cost-effective substitute for field surveys for IPS mapping and monitoring. Notwithstanding its benefits, IPSs are hard to detect at the species level because forest ecosystems have a complex and heterogeneous structure, and few distinctive spectral signs are available [70]. IPS mapping is further complicated due to variations in population density, phenology, and intermixing of spectra with native species across landscapes [81]. Identification of their distinctive spectral signatures, enabled by variations in biophysical and biochemical features, is crucial for the effectiveness of remote sensing for IPSs mapping [109]. However, when using broadband sensors with coarse to medium spatial resolution, plant species with similar spectral features may appear alike to the sensor if their differences are too small to increase spectral variance, which reduces the mapping accuracy of the target IPSs [61]. Furthermore, identifying IPSs can be difficult because they often grow alongside other plant species, especially in datasets with coarser spectral and spatial resolution.

For mapping the IPSs in various terrestrial ecosystems, several researchers have used a variety of remote sensing tools employing varied spatial-spectral-radiometric resolutions, including LANDSAT series of satellite images, SPOT, ASTER, SENTINEL 2A, IKONOS, QUCIKBIRD, Worldview 2 [29, 98, 109, 124, 147, 169, 176, 186]. Although these sensors offer high spatial resolution, they are less effective for mapping IPSs because their limited spectral capability makes it difficult to distinguish species, especially in dense and complex forest ecosystems. This has pushed ecologists to explore the potential of hyperspectral remote sensing with contiguous narrow spectral bands as available with ARIES-1, HySI, CHRIS, Hyperion, and PRISMA [32, 81]. Moreover, due to spaceborne configuration, these sensors are not effective in mapping the IPSs at a large scale, yet they are potentially effective in delineating the regional spread of IPSs, particularly of the large clusters and in open sky view. A few series of missions of airborne hyperspectral sensors are profoundly used for forest species discrimination and spread of IPSs in the forest very effectively and efficiently due to their differentiating capability between sophisticated inter- and intra-species spectral differences with the better spectral resolution, in which the airborne missions of AVIRIS-classical, AVIRIS-NG, AIMS, HYDICE, and HyMAP are very popular [4, 64, 82, 181] (Table 4).

Other cutting-edge techniques used by various researchers for mapping IPSs include artificial neural networks, spectral unmixing, spectral angle mapper (SAM), support vector machine (SVM), and Mahalanobis distance. By combining optical, microwave, hyperspectral, and LiDAR data, it has been possible to precisely map IPSs, which has strained the limits of current remote sensing techniques [75, 80, 132]. Moreover, the airborne deployment of a high-end mapping system with LiDAR and AVIRIS and its integration with field inventories are effectively being utilized to estimate the spread of highly invasive tree species [31]. However, the timing of data acquisition and seasonality of the invasive species with reference to the dominant tree species in that region is equally important and is considered while mapping the IPSs. The leafless period of dominant tree species and the mature status of IPSs is one of the ideal times to delineate the IPSs spread precisely [81]

7.1 Hyperspectral remote sensing for IPS mapping

Hyperspectral remote sensing sensors have a higher spectral resolution compared to conventional multispectral sensors, enabling the detection of minute spectrum differences in plant communities, which may be used to recognise IPSs and the extent of their spread [141]. Since IPSs frequently have distinctive spectral signatures that differ from the surrounding vegetation, this in-depth information can be utilized to distinguish IPSs from other vegetation types. Several cutting-edge methods can be used for IPS mapping using hyperspectral remote sensing data, such as machine learning methods like random forests, support vector machines, and neural networks [9, 97, 128]. These algorithms are capable of successfully classifying IPSs in massive datasets by learning to recognise the

Table 4 Comparison of multispectral and hyperspectral remote sensing for invasive plant species mapping

Parameter	Multispectral	Hyperspectral
Spectral resolution	Few broad bands (e.g., 4–13; ~ 30–100 nm)	Hundreds of narrow bands (~ 5–10 nm)
Spatial resolution	Medium to high (10–30 m; < 1 m for some commercial)	Often high (1–5 m airborne; ~ 30 m spaceborne)
Data availability	High; free (e.g., Landsat, Sentinel-2)	Limited; airborne/specialised missions, often costly
Processing complexity	Low to moderate	High (large data volume, complex algorithms)
Ability to discriminate spectrally similar species	Moderate	Very High
Temporal coverage	Frequent revisits (5–16 days)	Limited (mission/event-based)
Best suited for	Regional-scale mapping, change detection	Fine-scale mapping, biochemical trait analysis, early detection
Examples	LANDSAT series, SPOT, ASTER, SENTINEL 2, IKONOS, QUCIKBIRD, Worldview 2	ARIES-1, HySI, CHRIS, Hyperion, PRISMA, AVIRIS-NG, AIMS, HYDICE, and HyMAP

spectral patterns connected to them. Object-based image analysis (OBIA) is a method that groups meaningful objects out of pixels with similar spectral qualities via picture segmentation [101]. It may be used to map IPSs and categorize different vegetation types based on their geographical context, shapes, and sizes [147]. Spectral mixture analysis (SMA) is a method for breaking down hyperspectral data into discrete spectra that each reflect a particular endmember, such as plant, soil, or water. SMA may be used to identify IPSs by separating the IPSs based on their distinctive spectral signature from the surrounding vegetation. It may also provide estimates of the fractional abundance of different plant species in a scene, which can be used to evaluate the severity of an invasion [31]. By comparing hyperspectral data from various periods, it is possible to locate regions where IPSs are becoming more prevalent and track invasion dynamics over time following the changes in plant cover. Based on the literature review, some of the interesting works on IPSs mapping using hyperspectral data have been summarized in Table 5**.**

A recent study conducted in Mudumalai Tiger Reserve (MTR), Western Ghats, India, focused on mapping the distribution of understorey IPSs (*L. camara* and *C. odorata*) by differentiating IPSs from native dominant tree species using a very high-resolution airborne imaging spectroscopy (AVIRIS-NG) dataset [81]. They have used Sentinel-1A SAR data to identify a perfect window while canopy vegetation has little to no leaves (during leaf-shedding periods of deciduous trees) to solve the issue of canopy blockage, which prevents the hyperspectral data from detecting understorey species. The field spectra of selected IPSs and ten dominant native tree species were collected using an ASD FieldSpec 4 spectroradiometer. Later on, the pure pixels from AVIRIS-NG (extracted using pixel purity index) and field spectral data were used to create a spectral library for MESMA (Multiple Endmember Spectral Mixture Analysis) input using three indices: (a) Count-based Endmember Selection Index (CoBI), (b) Minimum Average Spectral Angle (MASA), and (c) Endmember Average RMSE (EAR). Finally, the MESMA technique was executed to extract the presence percentage of both the IPSs in every pixel. The results highlighted the large spatial distribution of both invasive species in the Mudumalai. The high invasion of *L. camara* was reported along with the dominance of tree species (Fig. 7) *Terminalia anogeissiana* Gere & Boatwr. and *Tectona grandis* L.f., while *C. odorata* was predominantly found with *T. anogeissiana* and *Terminalia elliptica* Willd.

7.2 Challenges of RS in mapping IPS

The forest canopy layers and their density used to pose a challenge to identify and precisely map IPSs employing remote sensing techniques. The majority of the IPSs are undergrowth and used to be prevalent in zones with damaged or open canopies, which might produce a distinct reflectance pattern. IPSs show competitive aggression and increased encroachment in disturbed environments since there is less interspecies competition when the soils are either left bare or the native flora is still in the early stages of rejuvenation [63]. Remote sensing data can be more useful for mapping IPSs in open forests or forest borders where there is less interference from the forest canopy and better sight of the understorey vegetation. Additionally, various IPSs may have different interactions with the layers of the forest canopy. For instance, some IPSs may colonize damaged areas of the understorey of the forest, while others may grow thick stands that alter the composition of species and the structure of the canopy. These IPSs could

Table 5 Overview of studies for IPS mapping using hyperspectral remote sensing

Study area	Sensor (properties)	Methods	Invasive species	References
Southern California, USA	AVIRIS (224, 10 nm, 4 m)	Continuum-Removal (CR), Minimum Noise Fraction (MNF) and Band ratioing, Spectral Angle Mapper (SAM), Unsupervised (K-means and isodata) Classification and Maximum Likelihood Classification (MLC)	*Carpobrotus edulis* (L.) N.E.Br., *Cortaderia jubata* (Lemoine) Stapf, *Foeniculum vulgare* Mill., *Arundo donax* L.	[172]
Farragut State Park near Bayview, Idaho	Probe-1 (128, 12-16 nm, 5 m)	SAM	*Centaurea maculosa* Noë ex Nyman	[96]
Madison County, Montana	Probe-1(128, 12-16 nm, 5 m)	Beiman Cutler Classifications (BCC) and Random Forest (RF)	*Euphorbia esula* L., *C. maculosa*	[97]
Sacramento–San Joaquin River Delta, USA	HyMap (128, 10-20 nm, 3 m)	MNF and Decision Tree	*Lepidium latifolium* L., *Pontederia crassipes* Mart.	[56]
Island of Hawaii	AVIRIS (224, 10 nm, 3 m)	Automated Spectral Mixture Analysis. (AutoSMA)	*Fraxinus uhdei* (Wenz.) Lingelsh., *Myrica faya* Aiton	[7]
Island of Hawaii	AVIRIS (224, 10 nm, 3 m)	Reflectance and derivative reflectance signatures	*Falcataria falcata* (L.) Greuter & R.Rankin, *M. faya*, *Casuarina equisetifolia* L.	[8]
Belton, central Texas	Airborne hyperspectral imaging system (128, 640 pixels)	Mixture Tuned Matched Filtering (MTMF)	*Juniperus ashei* J.Buchholz, *Gutierrezia sarothrae* (Pursh) Britton & Rusby, *P. crassipes*	[187]
KwaZulu Natal, South Africa	AISA Eagle (272, 2.4 m)	SVM	*Solanum mauritianum* Scop.	[9]
Hawai'i Volcanoes National Park	Hyperion (242, 10 nm, 30 m)	Spectral Separability Index (SI) and Multiple Endmember Spectral Mixture Analysis (MESMA)	*M. faya*, *Psidium cattleyanum* Sabine	[164]
Atlantic and Mediterranean coasts, Spain	Ultralight Airborne Imaging Spectroscopy (200, 3 nm)	SVM	*Acacia melanoxylon* R.Br., *Oxalis pescaprae* L., *C. edulis* (L.) N.E.Br., *Carpobrotus acinaciformis* (L.) L.Bolus	[18]
Surrey, British Columbia, Canada	CASI (72, 9.6 nm, 1 m)	Instability Index, SAM	*Rubus armeniacus* Focke, *Hedera helix* L.	[20]
West Virginia, USA	ASD FieldSpec FR 3 (1 nm)	SVM	*Ailanthus altissima* (Mill.) Swingle, *Carduus acanthoides* L., *Celastrus orbiculatus* Thunb., *Cirsium arvense* (L.) Scop., *Galium verum* L., *Rhamnus davurica* Pall.	[3]
Island of Sylt, Germany	APEX (Airborne Prism EXperiment) sensor (285, 1.8 m)	Maxent	*Campylopus introflexus* (Hedw.) Brid.	[163]
Portugal	AISA Eagle and Hawk (2 m)	RF	*Acacia longifolia* (Andrews) Willd.	[51]
Silesia Upland, Poland	HySpex (470, 1 m)	MNF, RF	*Molinia caerulea* (L.) Moench, *Calamagrostis epigejos* (L.) Roth	[107]
KwaZulu-Natal, South Africa	ASD FieldSpec FR 3 (1 nm)	Interval Extended Canonical Variate Discriminant (iECVA-DA), Random Forest Discriminant Classifiers (RF-DA)	*Acacia mearnsii* De Wild.	[108]

Table 5 (continued)

Study area	Sensor (properties)	Methods	Invasive species	References
Western Ghats, India	AVIRIS-NG (430, 5 nm, 4 m)	SVM, Classification and Regression Trees (CART), RF	*Acacia* spp., *Eucalyptus* spp., *Pinus* spp.	[4]
Koffler Scientific Reserve, Ontario, Canada	Micro-Hyperspec VNIR (325, 2 nm 0.2 m)	RF	*Bromus inermis, Dactylis glomerata*	[33]
Guangzhou city, China	Imaging spectrograph S185 (138, 4 nm)	PCA, RF and SVM	*M. micrantha*	[62]
Punjab, Pakistan	ASD FieldSpec handheld2 (751, 3 nm)	Hyperspectral indices and Spectral Separability Analysis	*P. hysterophorus, Prosopis juliflora* (Sw.) DC., *Leucaena leucocephala* (Lam.) de Wit, *L. camara*	[67]
Kiskunság National Park	UAV Hyperspectral Sensor (138, 4 nm, 40 cm)	SVM, Artificial Neural Network (ANN)	*Asclepias syriaca* L.	[128]
Western Ghats, India	AVIRIS-NG (430, 5 nm, 4 m)	MESMA	*L. camara, C. odorata*	[81]
Southern Poland	HySpex scanners (430, 1 m)	MNF, SVM	*C. epigejos, Rubus* spp., *Solidago* spp.	[149]
Quarta Colonia State Park, Brazil	ASD FieldSpec (3 nm)	Linear discriminant analysis (LDA)	*Hovenia dulcis* Thunb., *Psidium guajava* L.	[104]

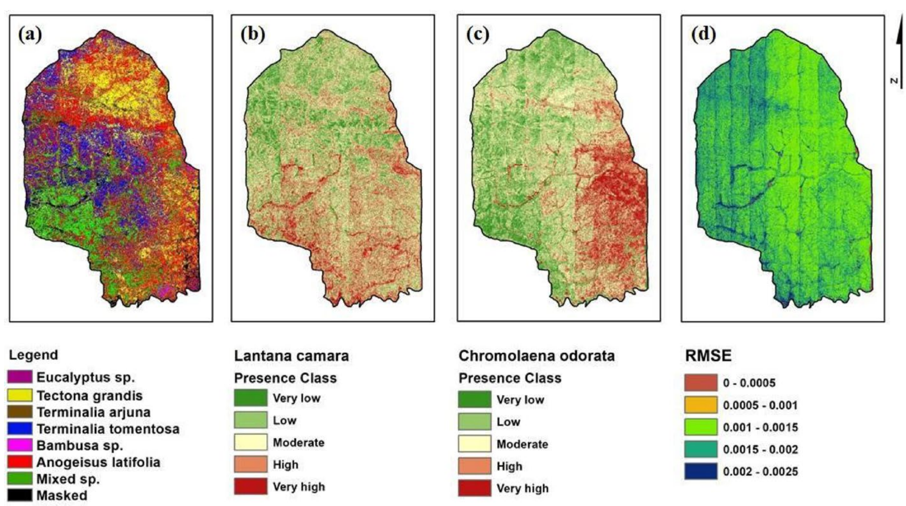

Fig. 7 Presence of IPSs *L. camara* and *C. odorata* alongside dominant tree species (reproduced from [81])

produce distinctive spectral signatures, making it necessary to map them using a variety of remote sensing techniques. Invasive tree species, *Acacia mearnsii* De Wild. with a height of 10-20 m and an open canopy, it can be mapped similarly to other canopy tree species using hyperspectral data [4]. While understorey species like *L. camara* and *C. odorata* with canopy influence are difficult to identify, this can be overcome by monitoring the phenological variations of the forest [81]. The cluster size of the IPSs must also be taken into consideration for accurate IPS mapping. It is difficult to distinguish IPSs in small clusters with an area smaller than the size of the sensor's pixels because of the mixed reflectance of nearby species in the pixel [122]. The thumb rule is to use high spatial resolution data so as to get a pure spectral profile of IPSs (Fig. 8).

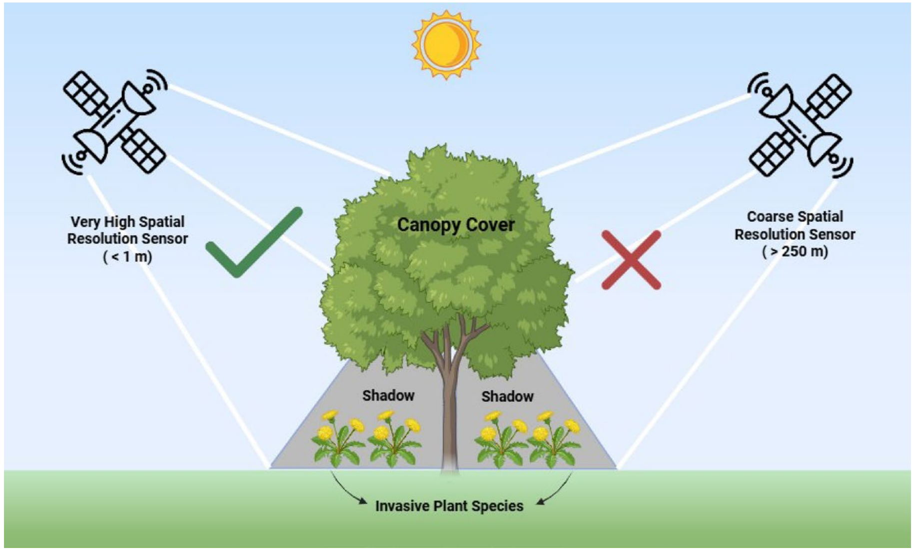

Fig. 8 Challenges of remote sensing in mapping invasive plant species, highlighting key constraints such as dense canopy cover, shadowed areas, and coarse spatial resolution

The extremely high spatial resolution and flexible gathering techniques of Unmanned Aerial Vehicles (UAVs) have recently made it more difficult to map IPSs. One of the drawbacks of pixel-based studies is the increase in spectral variability within class caused by canopy structure and shadows, which frequently makes it difficult to distinguish between classes [100]. Shadows are created when light is blocked, which reduces reflectivity. Diffuse radiation from light reflected from nearby objects or the atmosphere is absorbed by cast shadows in vegetated areas. In reality, a canopy's spectral signal may be diminished or lost entirely due to shadows [100], which has an impact on classification tasks [99]. Consideration must be given to the best time of day to acquire the image because shadows can occasionally completely obscure the area of interest at certain times of the day [111]. As a result, in order to accurately map IPSs in forested areas, it is essential to consider the spatial and spectral resolution of the remote sensing data, the distribution of the forest layer, and the characteristics of the IPSs and native species themselves. Remote sensing data may be used to detect locations with high invasion risk and to devise management strategies to control or eradicate IPSs before they attain their reproductive phases.

Best practices for remote sensing-based mapping of IPSs include using sensors and data resolutions that are appropriate for the target species spectral and spatial properties. Hyperspectral sensors with contiguous narrow bands are ideal for species level discrimination, especially in dense and varied forest environments, whereas multispectral data are appropriate for larger area monitoring. The combination of multi-sensor datasets (optical, microwave, LiDAR) with sophisticated analytical approaches such as spectral unmixing, OBIA, and machine learning enhances classification accuracy. Airborne hyperspectral missions such as AVIRIS-NG have shown useful in detecting small inter- and intra-species spectral changes, particularly when timed to coincide with phenological periods that promote IPS and native vegetation separability.

8 Restoration of forests degraded by invasives

Managing IPSs and preserving the health and component biodiversity of restored ecosystems needed significant financial investment worldwide [42]. Revegetation approaches as a part of restoration ecology have been initiated worldwide to minimize the effects of climate change, safeguard coastal populations, habitat and biodiversity restoration, mitigate invasive populations, and improve the quality of air and water [133]. Effective restoration required significant physical and environmental goals, comprehensive details of past and present anthropogenic activities on different biogeochemical cycles, primary data based on required objectives, prior functional characteristics of the ecosystems, and a proper extended planning, monitoring, and implementation programme [144]. Ecological indicators, adaptive frameworks, and long-term data collection serves as the foundation for monitoring strategies for the restoration of forests damaged by IPSs [123]. Establishing baseline ecosystems to measure recovery and concentrating on indicators such as vegetation structure, native species richness, regeneration of native species, and other functional features that represent ecosystem processes is the fundamental component of effective monitoring [184]. Methods and tools such as remote sensing technology, plot survey, and photo monitoring are significantly used for periodically monitoring of the changes in forest composition and canopy dynamics [123]. Whereas, adaptive management is a key component of these initiatives that enables restoration strategies to change in response to ecological feedback [106]. “Recovery Wheel” and “Restoration Opportunities Assessment Methodology (ROAM” of Society for Ecological Restoration and IUCN are some of the systematic strategies for progress assessment [68, 184]. Additionally, incorporating community involvement, hydrological metrics, and soil health improves the stability of monitoring [123]. Hence, implementation of uniform processes, protocols, policy, and long-term commitments will precisely monitor the restoration process. Replantation of long-term indigenous vegetation is the most effective nature-based solution for the management and eradication of IPSs worldwide out of various physical, chemical, and biological management strategies [60]. Ecosystems will be vulnerable to re-invasion by the same IPSs or other IPSs if vegetation is unable to establish due to inadequate natural regeneration [137]. In India, community led- restoration programmes were also recorded such as local and indigenous communities in Gadchiroli, Maharashtra, restoring the degraded forests, sustaining a supply of tendu leaves for bidi (Indian tobacco) (Impact [65]). Likewise, in Bandipur National Park and part of the Nilgiri Biosphere Reserve, Junglescapes: Restoring forests to conserve wildlife in India’s Western Ghats, a project that provide training to the locals for removal of *L. camara* from 2007, it has restored 1,300 hectares of degraded forests by providing employment to 45–70 community members throughout the year by simultaneously contributing in the restoration of wildlife habitats and empowerment of communities as environmental stewards [175]. A similar case was also recorded in Kuchchh grassland, Gujarat where locals actively participated in restoration of native grassland by removing IPSs (Impact [65]). Foundation for Ecological Security along with Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), IKEA Foundation, Madhya Pradesh Forest Department, National Bank for Agriculture and Rural Development (NABARD), Natwest Foundation, and UN Climate Adaptation Fund by working local farmers and community members, restored 6078 hectares of land by removing *L. camara* in Mandla and Balaghat, Madhya Pradesh [94]. Hence, promoting native species will prevent the invasion of IPSs by increasing pressure on the regeneration of indigenous propagules and thereby reducing the IPS population [11].

9 Policy interventions for the management of IPS to achieve UN-SDGs

The management of IPSs is crucial and complicated, with greater economic and ecological implications [188]. Numerous methods are employed for the control and management of IPSs globally, of which the majority are unsuccessful in effectively limiting the spread of IPSs [14] (Fig. 9). The removal of above-ground biomass or burning is one of the common traditional control measures that are momentarily beneficial but cause excessive coppicing after rain, while uprooting IPSs or destroying the coppicing meristem is a highly effective control measure [10]. Understanding the various environmental conditions will help to know the colonization periods of IPSs in different ways, which may further assist in choosing the best seasons, times of the year, or stages of invasion that will be controlled and managed [142]. Increasing awareness among communities, maintaining forests, early detection, and acquiring restoration approaches are used as strategies to control biological invasions [113]. Non-chemical approaches simply remove the plants' shoots and are unable to inhibit resprouting from the ground, but some herbicides permanently suppress the IPS growth [43]. Forests and other ecosystems that are highly diverse are less susceptible to IPSs [145]. Hence, the management, eradication, and control of IPSs will help in sustaining forest biodiversity and devising management and development strategies [160]. To control IPSs, repeated treatment of herbicides in combination with new active ingredients is applied at an ideal rate in various countries [151]. The endorsement of integrated pest management (IPM) systems should be put forward for managing plant incursions with reference to ecological farming and thereby taking proper precautions for the health of the soil, plants, animals, and the environment [168]. The best way to comprehend the significance and implications of the long-term management of IPSs is to focus on the goals and recommendations made in policies and strategies [47, 52]. Countries throughout the world have set ambitious restoration commitments, pledging to support the restoration of the forest landscape on 170 Mha by 2030 [22]. Early detection and location-specific management systems for the eradication of IPSs are one of the efficient and quick responses to the control of invasion [168]. In addition, 2021–2030 is declared as the ecosystem restoration

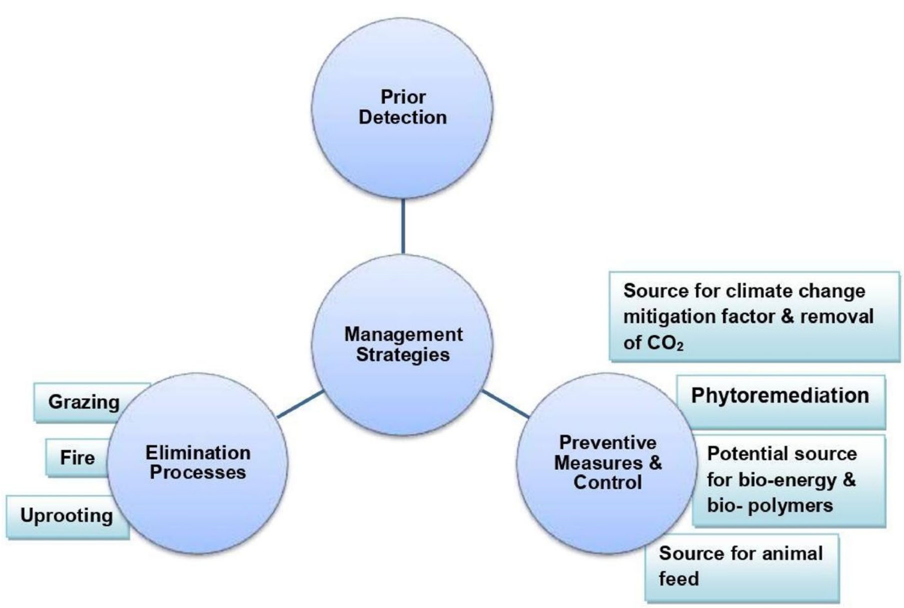

Fig. 9 Management strategies for control and regulation of IPSs

decade by the United Nations, which helps mainstream global investments in upscaling the restoration of various native ecosystems [185]. Impact-based IPS initiatives and policies are also intimately related to ecological sustainability and the SDGs. On a global scale, a huge number of countries implement applicable national legislation and adequately finance the prevention and control of IPSs as an indicator for achieving the UN-SDG target 15.8, which deals with minimizing the negative effects and removing or controlling the IPSs on terrestrial and aquatic ecosystems [47]. Target 9 of Aichi's biodiversity and zero drafts of the post-2020 Global Biodiversity Framework under the CBD Act state that IPSs constitute a major threat to ecological services and biodiversity, suggesting priority control of IPSs [24, 25]. Target 3 of the 2030 Action Plan aimed to manage, reduce, and eradicate IPSs by at least 50% [47]. Global Assessment based on IPSs was also introduced in the seventh symposium of the IPBES [17].

10 Recommendations and future research prospects

- Anthropogenic disruptions are the main cause of biological invasions, and if human-mediated perturbations continue for a long time, a new IPS may appear that poses risks to both human and environmental health.
- IPSs can be managed sustainably by a clear understanding of the numerous dynamics that contribute to their spread, occurrence, and establishment.
- For a better understanding of the rate of biodiversity loss due to IPSs, the study of biochemical mechanisms of native-IPSs interactions should be prioritized.
- Also, future management work on IPSs should focus on the socioeconomic aspects for cost–benefit analysis, which is important for future research in ensuring the advantages to livelihood.
- Long-term monitoring with regular evaluation on international levels should be implemented to monitor and restrict the spread of IPSs.
- Using sophisticated tools and cutting-edge technology will help to manage IPSs and support farmers, agricultural consultants, researchers, and advisory committees in their decision-making.

11 Conclusions

The increase in plant invasions in forest ecosystems is caused by both climate change and anthropogenic disturbances. IPSs likely harm native biodiversity and ecological services. Physical, chemical, and soil property changes caused by invasives can have a significant impact on forest composition and regeneration. An efficient approach for managing IPSs should have risk assessment and dispersion prediction models along with the enforcement of preventive procedures to avoid plant invasion, site-specific measures to eradicate or reduce the impact of IPSs, implementation of strategies for preventing the spread of IPSs, and other actions required to reduce IPSs. To minimize the impact of harmful IPSs, improvements in non-chemical equipment, renewable and modern technology, cultivation methods, and the ability of crops to compete against IPSs should be introduced on a broad scale. Further, the IPM system must be renewed to monitor and mitigate the impacts of IPSs with respect to their precision, efficiency, economic feasibility, community acceptability, and ecological compatibility to lessen their impacts.

Appendix

See Appendix Tables 6 and 7.

Table 6 List of IPS with their origin and sources documented in India

Species	Family	Origin	Sources
Acacia longifolia (Andrews) Willd.	Fabaceae	South-East Australia[1]	GISD
Acacia mearnsii De Wild.	Fabaceae	South-East Australia[1]	GISD, ENVIS
Acacia melanoxylon R.Br.	Fabaceae	Eastern Australia[1]	GISD
Acacia pycnantha Benth.	Fabaceae	Eastern Australia[2]	GISD
Acacia retinodes Schltdl.	Fabaceae	Australia[3]	GISD
Acanthospermum hispidum DC.	Asteraceae	Brazil[3]	ENVIS
Acmella oleracea (L.) R.K.Jansen	Asteraceae	South-East Brazil[4]	ENVIS
Aeschynomene americana L.	Fabaceae	Tropical and Sub-tropical America[4]	ENVIS
Agave americana L.	Asparagaceae	Mexico and Southern USA[5]	GISD
Ageratina adenophora (Spreng.) R.M.King & H.Rob.	Asteraceae	Tropical America[3]	ENVIS
Ageratum conyzoides L.	Asteraceae	Tropical America[3]	GISD, ENVIS
Ageratum houstonianum Mill.	Asteraceae	Tropical America[3]	ENVIS
Alternanthera ficoidea (L.) P.Beauv.	Amaranthaceae	Tropical America[4]	ENVIS
Alternanthera paronychioides A.St.-Hil.	Amaranthaceae	Tropical America[3]	ENVIS
Alternanthera philoxeroides (Mart.) Griseb.	Amaranthaceae	Tropical America[3]	GISD, ENVIS
Alternanthera pungens Kunth	Amaranthaceae	Tropical America[3]	ENVIS
Ambrosia artemisiifolia L.	Asteraceae	Temperate North America[1]	GISD
Antigonon leptopus Hook. & Arn.	Polygonaceae	Tropical America[3]	ENVIS
Argemone mexicana L.	Papaveraceae	Tropical Central and South America[3]	ENVIS
Asclepias curassavica L.	Apocynaceae	Tropical America[3]	ENVIS
Asparagus densiflorus (Kunth) Jessop	Asparagaceae	Southern Africa[6]	GISD
Bambusa vulgaris Schrad. ex J.C.Wendl.	Poaceae	South- East Asia[6]	GISD
Bidens pilosa L.	Asteraceae	Tropical America[3]	ENVIS
Cabomba caroliniana A.Gray	Cabombaceae	South America[6]	GISD
Cardamine flexuosa With.	Brassicaceae	Europe[6]	GISD
Celosia argentea L.	Amaranthaceae	Tropical Africa[3]	ENVIS
Cenchrus clandestinus (Hochst. ex Chiov.) Morrone	Poaceae	Tropical Eastern Africa[1]	GISD
Cenchrus purpureus (Schumach.) Morrone	Poaceae	Tropical America[3]	ENVIS
Cestrum nocturnum L.	Solanaceae	Antilles and Central America[6]	GISD
Chamaecrista rotundifolia (Pers.) Greene	Fabaceae	Tropical South America[3]	ENVIS
Chromolaena odorata (L.) R.M.King & H.Rob.	Asteraceae	Tropical America[3]	GISD, ENVIS
Cirsium arvense (L.) Scop.	Asteraceae	Europe and Asia[6]	GISD
Crassocephalum crepidioides (Benth.) S.Moore	Asteraceae	Tropical America[3]	ENVIS
Croton bonplandianus Baill.	Euphorbiaceae	Temperate South America[3]	ENVIS
Cryptostegia grandiflora Roxb. ex R.Br.	Apocynaceae	Madagascar[3]	GISD, ENVIS
Cryptostegia madagascariensis Bojer ex Decne.	Apocynaceae	Madagascar[1]	GISD
Cyperus rotundus L.	Cyperaceae	Africa and Eurasia[7]	GISD
Cytisus scoparius (L.) Link	Fabaceae	Europe[3]	ENVIS
Datura innoxia Mill.	Solanaceae	Tropical America[3]	ENVIS
Datura metel L.	Solanaceae	Tropical America[3]	ENVIS
Decalobanthus peltatus (L.) A.R.Simões & Staples	Convolvulaceae	Tanzania[4]	GISD
Digera muricata (L.) Mart.	Amaranthaceae	South-West Asia[3]	ENVIS
Distimake aegyptius (L.) A.R.Simões & Staples	Convolvulaceae	Tropical America[3]	ENVIS
Distimake tuberosus (L.) A.R.Simões & Staples	Convolvulaceae	Tropical America[4]	GISD
Dolichandra unguis-cati (L.) L.G.Lohmann	Bignoniaceae	Tropical America[4]	GISD

Table 6 (continued)

Species	Family	Origin	Sources
Echinochloa crus-galli (L.) P.Beauv.	Poaceae	Tropical South America[3]	ENVIS
Eclipta prostrata (L.) L.	Asteraceae	Tropical America[3]	ENVIS
Elaeagnus umbellata Thunb.	Elaeagnaceae	East Asia[6]	GISD
Erigeron karvinskianus DC.	Asteraceae	Central and South America[8]	ENVIS
Eugenia uniflora L.	Myrtaceae	Tropical America[9]	GISD
Eupatorium cannabinum L.	Asteraceae	Ireland and UK[1]	GISD
Euphorbia cyathophora Murray	Euphorbiaceae	Tropical America[3]	ENVIS
Euphorbia heterophylla L.	Euphorbiaceae	Tropical America[3]	ENVIS
Euphorbia hirta L.	Euphorbiaceae	Tropical America[3]	ENVIS
Euphorbia umbellata (Pax) Bruyns	Euphorbiaceae	Tropical America[3]	ENVIS
Evolvulus nummularius (L.) L.	Convolvulaceae	Tropical America[3]	ENVIS
Festuca bromoides L.	Poaceae	Europe, North America and West Asia[4]	GISD
Flaveria trinervia (Spreng.) C.Mohr	Asteraceae	Tropical Central America[3]	ENVIS
Galinsoga parviflora Cav.	Asteraceae	Tropical America[3]	ENVIS
Gamochaeta americana (Mill.) Wedd.	Asteraceae	Tropical America[3]	ENVIS
Gamochaeta pensylvanica (Willd.) Cabrera	Asteraceae	Tropical America[3]	ENVIS
Gomphrena serrata L.	Amaranthaceae	Tropical America[3]	ENVIS
Gymnocoronis spilanthoides DC.	Asteraceae	Peru, Brazil, and North Argentina[4]	GISD
Heliotropium curassavicum L.	Boraginaceae	Tropical America[6]	GISD
Imperata cylindrica (L.) Raeusch.	Poaceae	Tropical America[3]	GISD, ENVIS
Ipomoea carnea Jacq.	Convolvulaceae	Tropical America[3]	ENVIS
Ipomoea hederifolia L.	Convolvulaceae	Tropical America[3]	ENVIS
Ipomoea quamoclit L.	Convolvulaceae	Tropical America[3]	ENVIS
Lagascea mollis Cav.	Asteraceae	Tropical Central America[3]	ENVIS
Lantana camara L.	Verbenaceae	Tropical America[3]	GISD, ENVIS
Launaea intybacea (Jacq.) Beauverd	Asteraceae	Africa[1]	GISD
Leucaena leucocephala (Lam.) de Wit	Fabaceae	Tropical America[3]	GISD, ENVIS
Limnocharis flava (L.) Buchenau	Alismataceae	America[1]	GISD
Lotus corniculatus L.	Fabaceae	Europe, Africa, and Asia[1]	GISD
Ludwigia octovalvis (Jacq.) P.H.Raven	Onagraceae	Tropical Africa[3]	ENVIS
Ludwigia peruviana (L.) H.Hara	Onagraceae	South Mexico and Tropical America[4]	GISD
Macroptilium lathyroides (L.) Urb.	Fabaceae	Tropical Central America[3]	ENVIS
Malachra capitata (L.) L.	Malvaceae	Tropical America[3]	ENVIS
Malvastrum coromandelianum (L.) Garcke	Malvaceae	Tropical America[3]	ENVIS
Martynia annua L.	Martyniaceae	Tropical America[3]	ENVIS
Mecardonia procumbens (Mill.) Small	Plantaginaceae	Tropical North America[3]	ENVIS
Melaleuca quinquenervia (Cav.) S.T.Blake	Myrtaceae	Australia and Eastern Asia[6]	GISD
Melilotus albus Medik.	Fabaceae	Europe and Asia[6]	ENVIS
Melinis repens (Willd.) Zizka	Poaceae	Tropical America[3]	ENVIS
Mesosphaerum suaveolens (L.) Kuntze	Lamiaceae	Tropical America[3]	ENVIS
Miconia crenata (Vahl) Michelang.	Melastomataceae	Tropical America[3]	ENVIS
Mikania micrantha Kunth	Asteraceae	Tropical America[3]	GISD, ENVIS
Mimosa diplotricha C.Wright	Fabaceae	Tropical and Sub-tropical America[4]	GISD
Mimosa pudica L.	Fabaceae	Brazil[3]	GISD, ENVIS
Mirabilis jalapa L.	Nyctaginaceae	Peru[3]	ENVIS

Table 6 (continued)

Species	Family	Origin	Sources
Nicotiana plumbaginifolia Viv.	Solanaceae	Tropical America[3]	ENVIS
Opuntia stricta (Haw.) Haw.	Cactaceae	Tropical America[3]	ENVIS
Oxalis corniculata L.	Oxalidaceae	Europe[3]	ENVIS
Oxalis latifolia Kunth	Oxalidaceae	North, Central, and South America[1]	GISD
Oxalis pes-caprae L.	Oxalidaceae	Southern Africa[1]	GISD
Parthenium hysterophorus L.	Asteraceae	Tropical North America[3]	GISD, ENVIS
Paspalum vaginatum Sw.	Poaceae	North America[1]	GISD
Passiflora foetida L.	Passifloraceae	Tropical South America[3]	ENVIS
Peperomia pellucida (L.) Kunth	Piperaceae	Tropical South America[3]	ENVIS
Phalaris arundinacea L.	Poaceae	North America[6]	GISD
Phyllanthus tenellus Roxb.	Phyllanthaceae	Mascarene Islands[3]	ENVIS
Physalis angulata L.	Solanaceae	Tropical America[3]	ENVIS
Physalis peruviana L.	Solanaceae	Brazil[4]	GISD
Physalis pruinosa L.	Solanaceae	Tropical America[3]	ENVIS
Pilea microphylla (L.) Liebm.	Urticaceae	Tropical South America[3]	ENVIS
Pittosporum undulatum Vent.	Pittosporaceae	South- East Australia[1]	GISD
Pontederia crassipes Mart.	Pontederiaceae	South America[1]	GISD
Portulaca oleracea L.	Portulacaceae	Tropical South America[3]	ENVIS
Prosopis juliflora (Sw.) DC.	Fabaceae	Mexico[3]	GISD, ENVIS
Prunus campanulata Maxim.	Rosaceae	China, Taiwan, and Vietnam[1]	GISD
Psidium guajava L.	Myrtaceae	Central America[1]	GISD
Ricinus communis L.	Euphorbiaceae	Tropical Africa[4]	GISD
Rubus moluccanus L.	Rosaceae	South- East Asia and Pacific[1]	GISD
Ruellia tuberosa L.	Acanthaceae	Tropical America[3]	ENVIS
Salvinia molesta D.Mitch.	Salviniaceae	Brazil[3]	GISD, ENVIS
Scaevola taccada (Gaertn.) Roxb.	Goodeniaceae	Pacific and Indian Ocean[1]	GISD
Scoparia dulcis L.	Plantaginaceae	Tropical America[3]	ENVIS
Senna alata (L.) Roxb.	Fabaceae	West Indies[3]	ENVIS
Senna hirsuta (L.) H.S.Irwin & Barneby	Fabaceae	Tropical America[3]	ENVIS
Senna obtusifolia (L.) H.S.Irwin & Barneby	Fabaceae	Tropical America[3]	ENVIS
Senna occidentalis (L.) Link	Fabaceae	Tropical South America[3]	ENVIS
Senna tora (L.) Roxb.	Fabaceae	Tropical South America[3]	ENVIS
Senna uniflora (Mill.) H.S.Irwin & Barneby	Fabaceae	Tropical South America[3]	ENVIS
Solanum americanum Mill.	Solanaceae	Tropical America[3]	ENVIS
Solanum mauritianum Scop.	Solanaceae	Brazil and Argentina[4]	GISD
Solanum seaforthianum Andrews	Solanaceae	Brazil[3]	ENVIS
Solanum sisymbriifolium Lam.	Solanaceae	South America[1]	GISD
Solanum torvum Sw.	Solanaceae	West Indies[3]	ENVIS
Solanum viarum Dunal	Solanaceae	Tropical America[3]	GISD, ENVIS
Sonchus asper (L.) Hill	Asteraceae	Mediterranean[3]	ENVIS
Sonchus oleraceus L.	Asteraceae	Mediterranean[3]	ENVIS
Sporobolus alterniflorus (Loisel.) P.M.Peterson & Saarela	Poaceae	Mexico[4]	GISD
Stachytarpheta jamaicensis (L.) Vahl	Verbenaceae	Tropical America[3]	ENVIS
Stachytarpheta urticifolia Sims	Verbenaceae	Tropical America[3]	ENVIS
Stylosanthes hamata (L.) Taub.	Fabaceae	Tropical America[3]	ENVIS
Synedrella nodiflora (L.) Gaertn.	Asteraceae	West Indies[3]	ENVIS

Table 6 (continued)

Species	Family	Origin	Sources
Tecomaria capensis (Thunb.) Spach	Bignoniaceae	South Africa[4]	GISD
Triadica sebifera (L.) Small	Euphorbiaceae	China[4]	GISD
Tridax procumbens L.	Asteraceae	Tropical Central America[3]	ENVIS
Turnera subulata Sm.	Passifloraceae	Tropical America[3]	ENVIS
Turnera ulmifolia L.	Passifloraceae	Tropical America[3]	ENVIS
Ulex europaeus L.	Fabaceae	Western Europe[3]	GISD, ENVIS
Vachellia farnesiana (L.) Wight & Arn.	Fabaceae	Tropical America[3]	GISD, ENVIS
Waltheria indica L.	Malvaceae	Tropical America[3]	ENVIS

[1]http://www.iucngisd.org/gisd/search.php

[2]https://florabase.dpaw.wa.gov.au/browse/profile/3504

[3]http://www.bsienvis.nic.in/database/invasive_alien_species_15896.aspx

[4]https://powo.science.kew.org/

[5]https://pza.sanbi.org/agave-americana#:~:text=Agave%20americana%20is%20native%20to,arid%20regions%20of%20the%20world

[6]http://www.worldfloraonline.org/

[7]https://www.ars-grin.gov/

[8]https://portal.wiktrop.org/species/show/135

[9]https://indiabiodiversity.org/species/show/264941

Table 7 Summary table of selected IPSs

Species Name	Growth Form	Key Features	Habitat Preference	Notable Impacts and Traits	Hotspots in India
Ageratum conyzoides L.	Herbaceous annual/perennial	Erect aromatic herb up to 1 m, soft pubescent leaves, blue/ mauve flowers	Cultivated fields, forests, wastelands, disturbed sites	Allelopathic, highly invasive, suppresses native flora, crop weed, rapid seed production	North-West Himalayas (Himachal Pradesh, Uttarakhand), Eastern Himalayas, Western Ghats, Central India, North-East India (Assam), widespread across Southern India
Lantana camara L.	Perennial woody shrub	Multicolored flowers, aromatic rough leaves, 2-5 m tall	Open/ disturbed lands, forests, agricultural margins	Highly invasive, toxic to livestock, forms dense thickets reducing biodiversity	Widespread in Southern and Central India, Western Ghats, North-Eastern states, parts of Maharashtra and Tamil Nadu
Parthenium hysterophorus L.	Herbaceous annual	Deeply lobed leaves, white flowers, erect up to 1.5 m	Fields, roadsides, wastelands	Causes human allergies and dermatitis, allelopathic, dense stands damaging crops and biodiversity	Widely distributed across India, especially Indo-Gangetic plains, Central and Southern India, Uttar Pradesh, Maharashtra, Tamil Nadu
Mesosphaerum suaveolens (L.) Kuntze.	Perennial herb/shrub	Aromatic leaves, fast-growing, purple flowers	Disturbed habitats, fallow lands	Allelopathic, displaces native vegetation, fast spread	Common in southern India including Tamil Nadu, Karnataka, Kerala, Central, and North-Eastern India
Chromolaena odorata (L.) R.M.King & H.Rob.	Perennial woody shrub	Soft hairy triangular leaves, pale blue flowers, up to 3 m	Forest edges, open woods, disturbed lands	Highly invasive, fire hazard, allelopathic, toxic to livestock	Western Ghats (Kerala, Karnataka, Tamil Nadu), North-Eastern states (Assam, Arunachal Pradesh), parts of central India (Madhya Pradesh), Maharashtra

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Author contributions
SP: participated in the literature collection, data analysis and presentation, and drafted the manuscript; BSPCK: contributed in the preparation of the map and drafting of the manuscript, especially the remote sensing inputs; PS and AK conceived the study and helped in finalizing the manuscript. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

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Not applicable.

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The authors declare no competing interests.

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